# Velocity field in the ICM: observational signatures and constraints

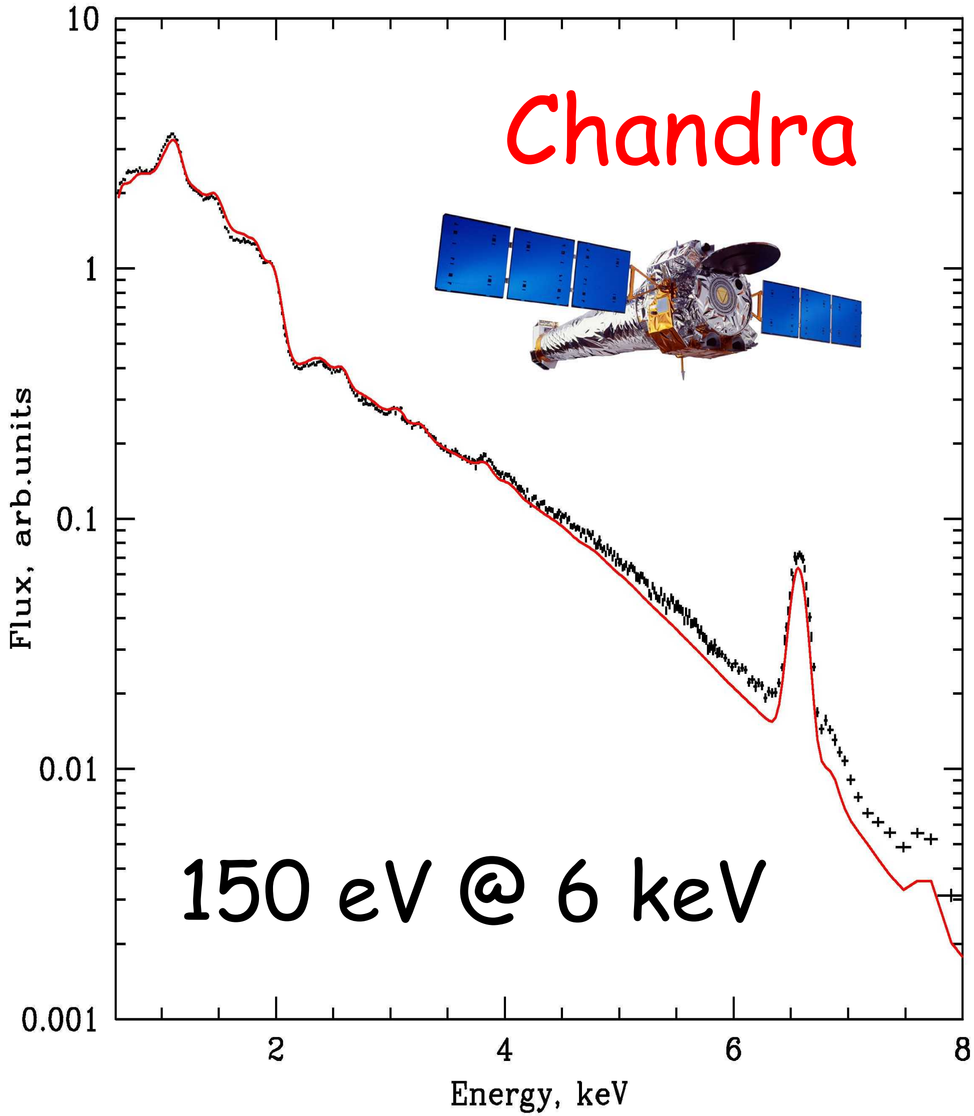
**What do we do with near future high energy resolution data (Astro-H)?**

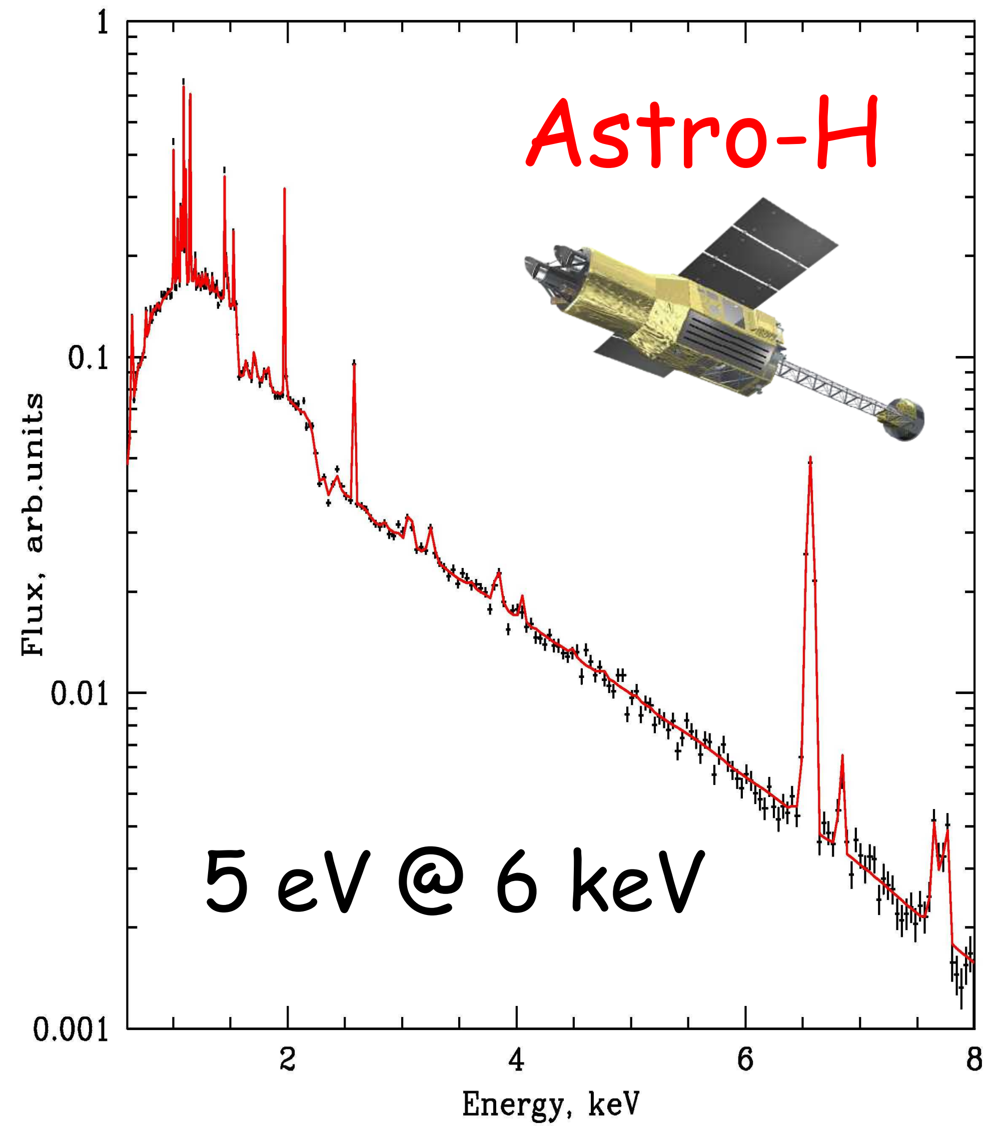
I. Zhuravleva, E. Churazov, A. Kravtsov, R. Sunyaev

(Zhuravleva+11, to be subm.)

# Direct velocity measurements

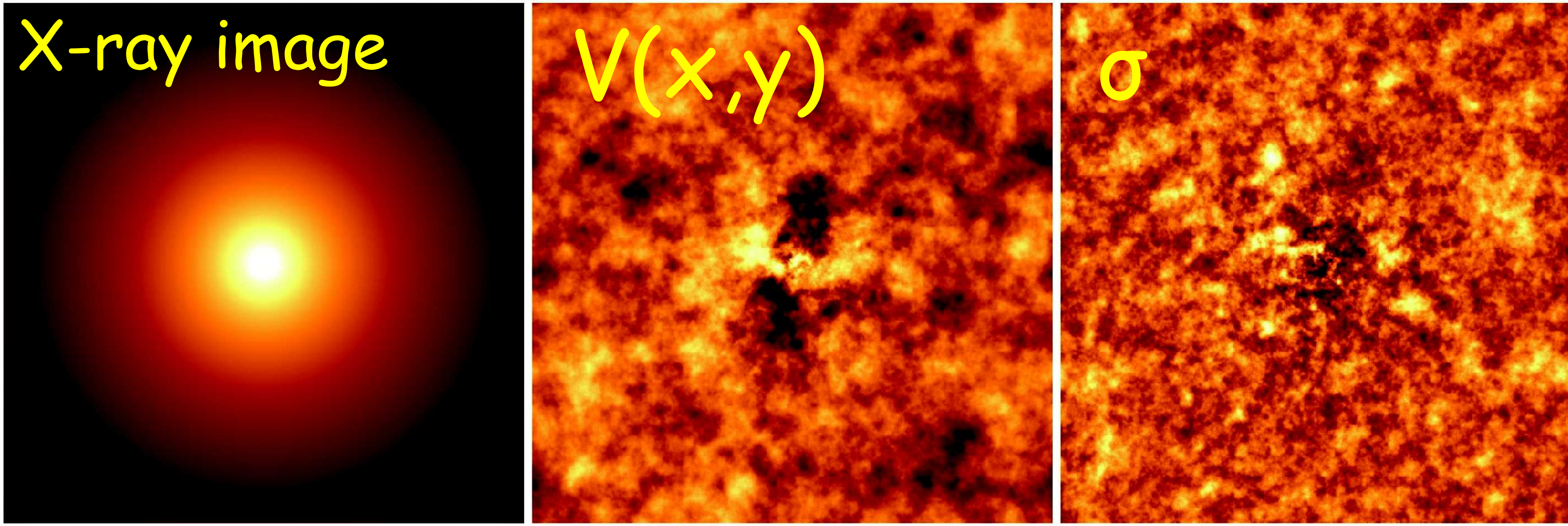
## Perseus cluster today and tomorrow



# Observables

**emissivity** | **shift of centroid** | **line width**



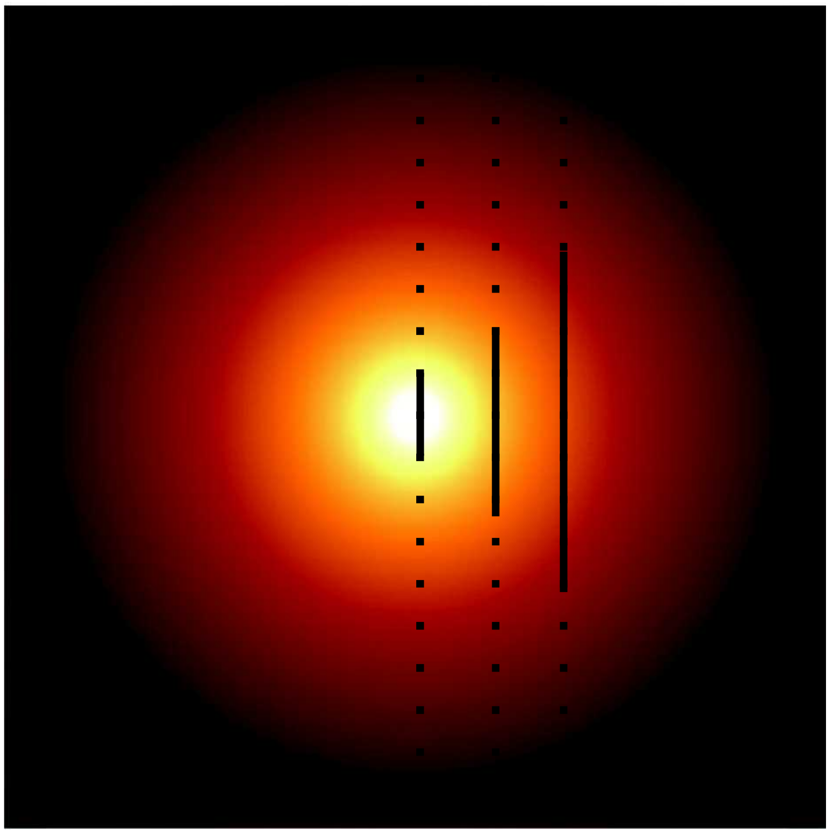

**Emissivity-weighted V and σ**

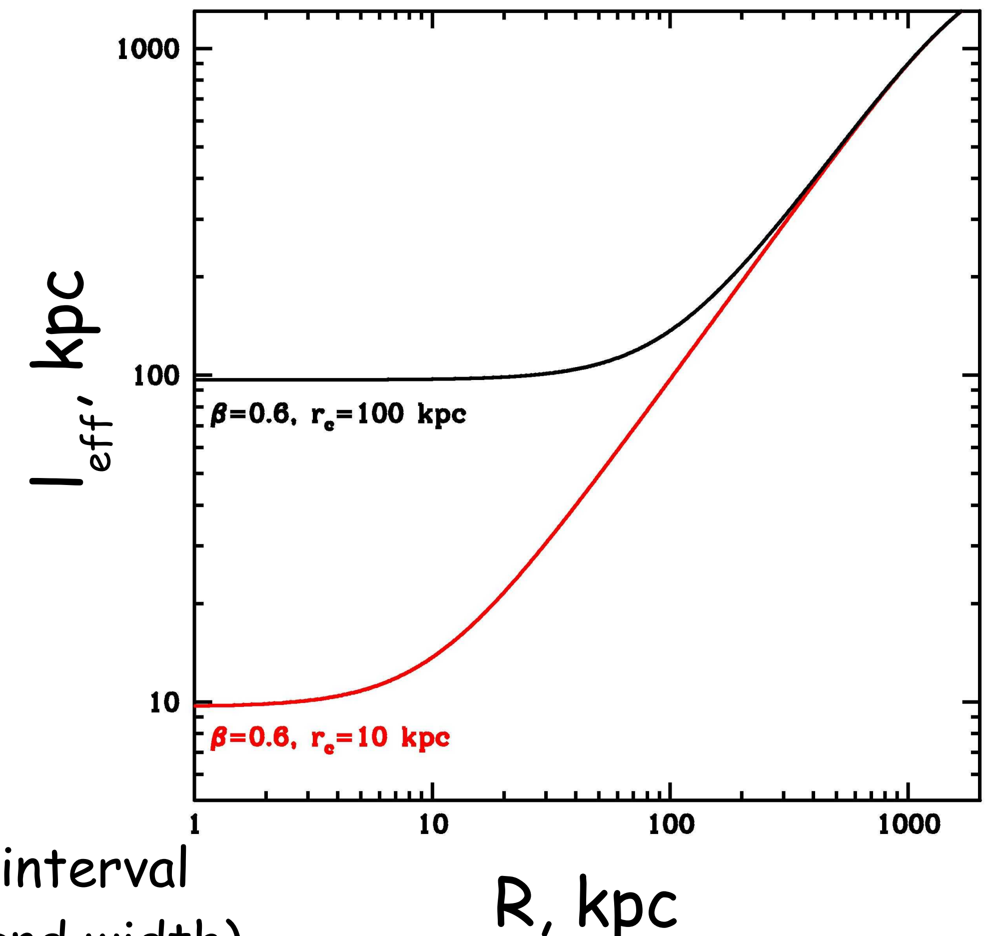
σ(R) → structure function of turbulence

RMS(V)/σ → correlation length of velocity field

# Observed σ and structure function

$$\mathrm{SF}(\Delta r) = \langle [V(r) - V(r+\Delta r)]^2 \rangle$$





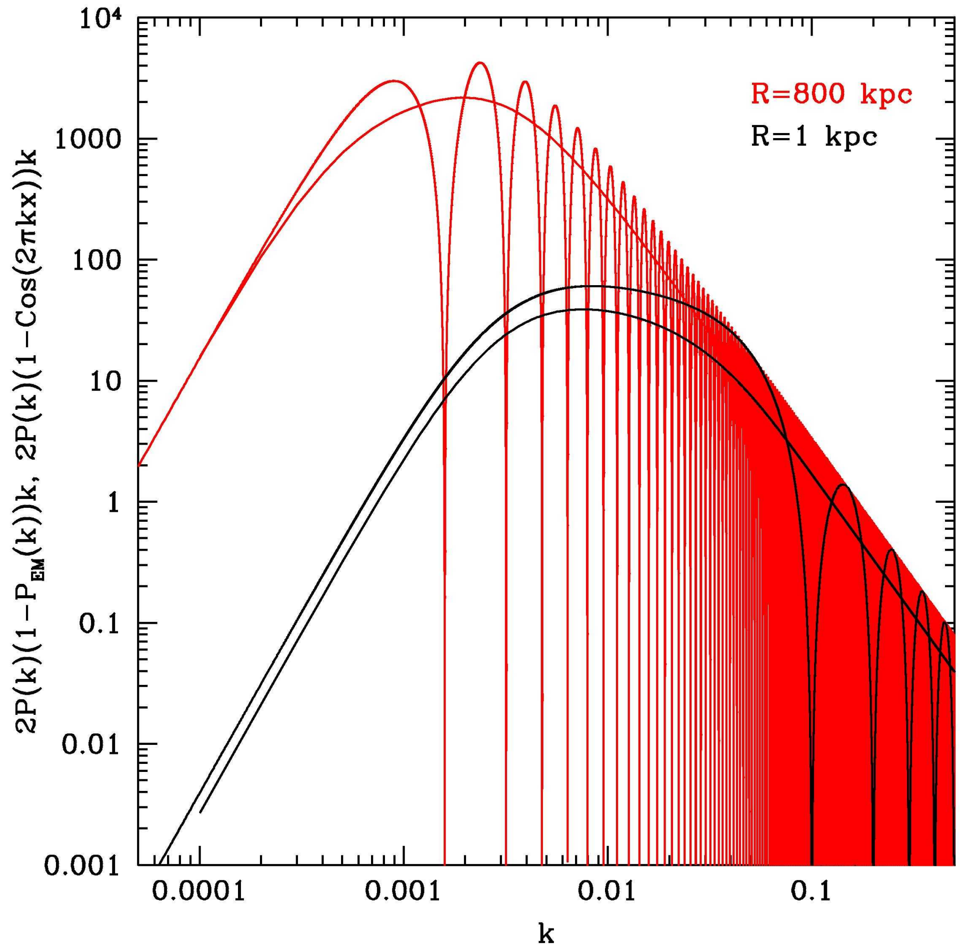

At a given projected distance R an interval $l_{eff}$ ~ R contributes to the line flux (and width)

**Observed σ(R) ≈ structure function ($l_{eff}$)**

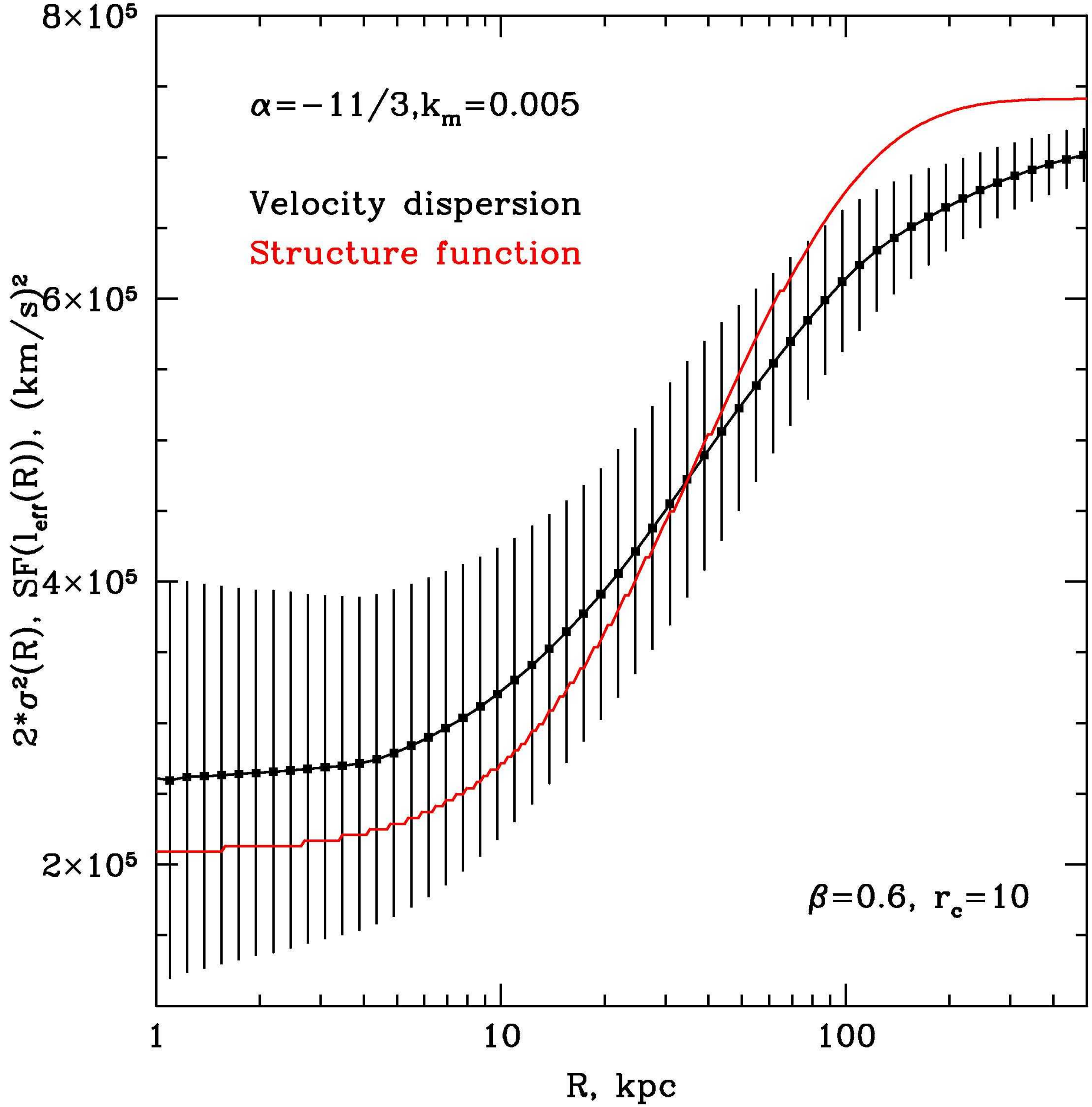
# Observed σ and structure function

$$SF(x) = 2\int_{-\infty}^{+\infty} P_{1\mathrm{D}}(k_z)(1-\cos 2\pi k_z x)dk_z$$

$$\sigma^2(R) = \int_{-\infty}^{+\infty} P_{1\mathrm{D}}(k_z)(1 - P_{\mathrm{EM}})dk_z$$



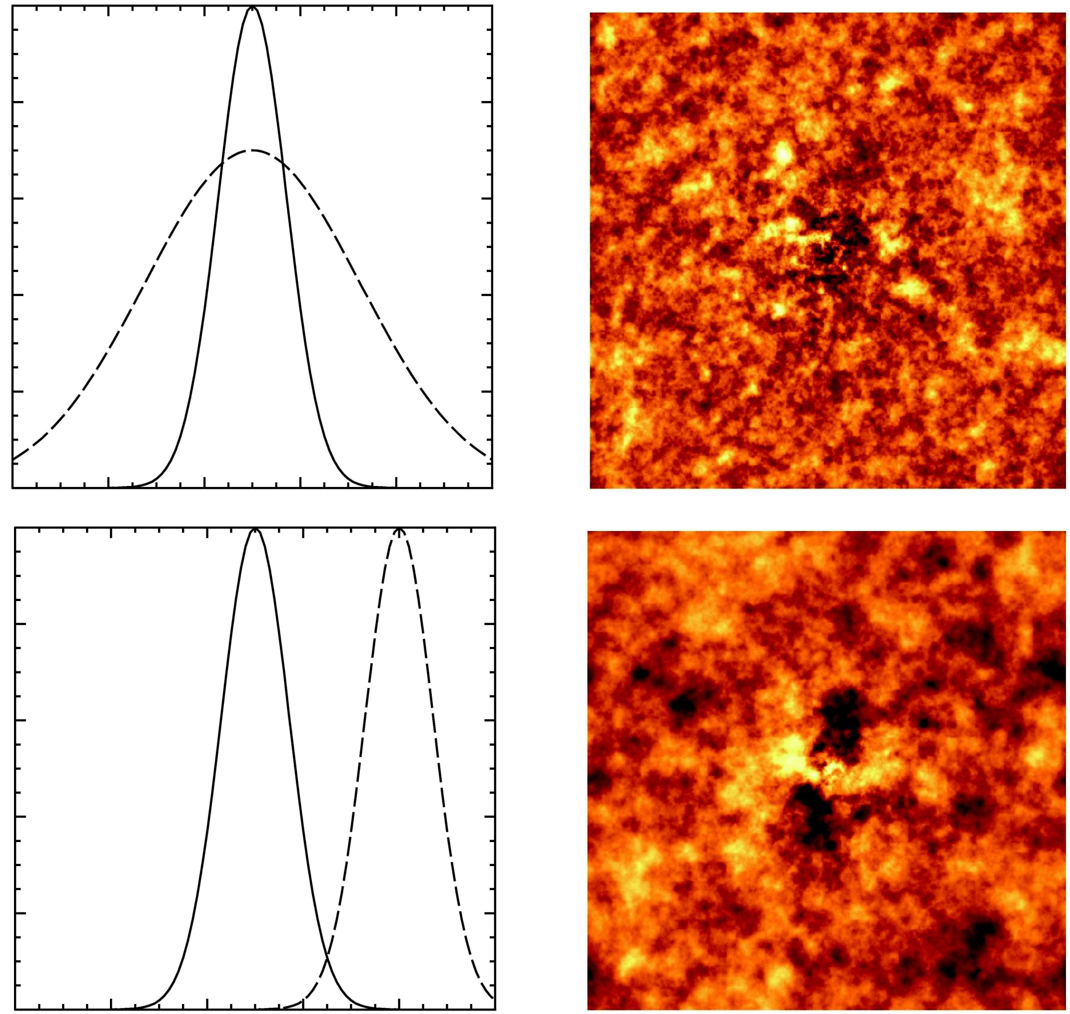
# Observed σ and structure function



# RMS(V) and correlation length

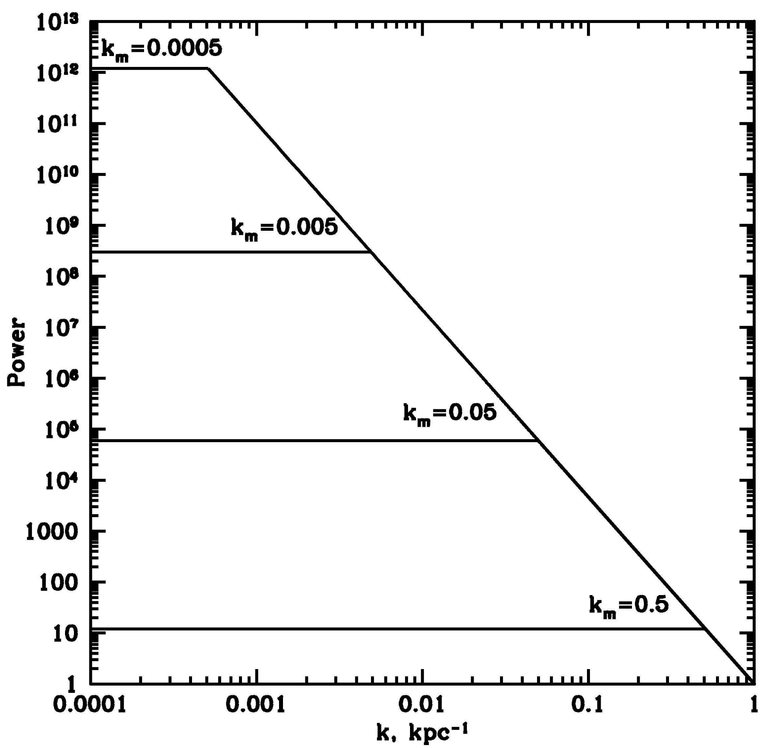
$V_{3D}$ → $L < L_{eff}$ : $\sigma$

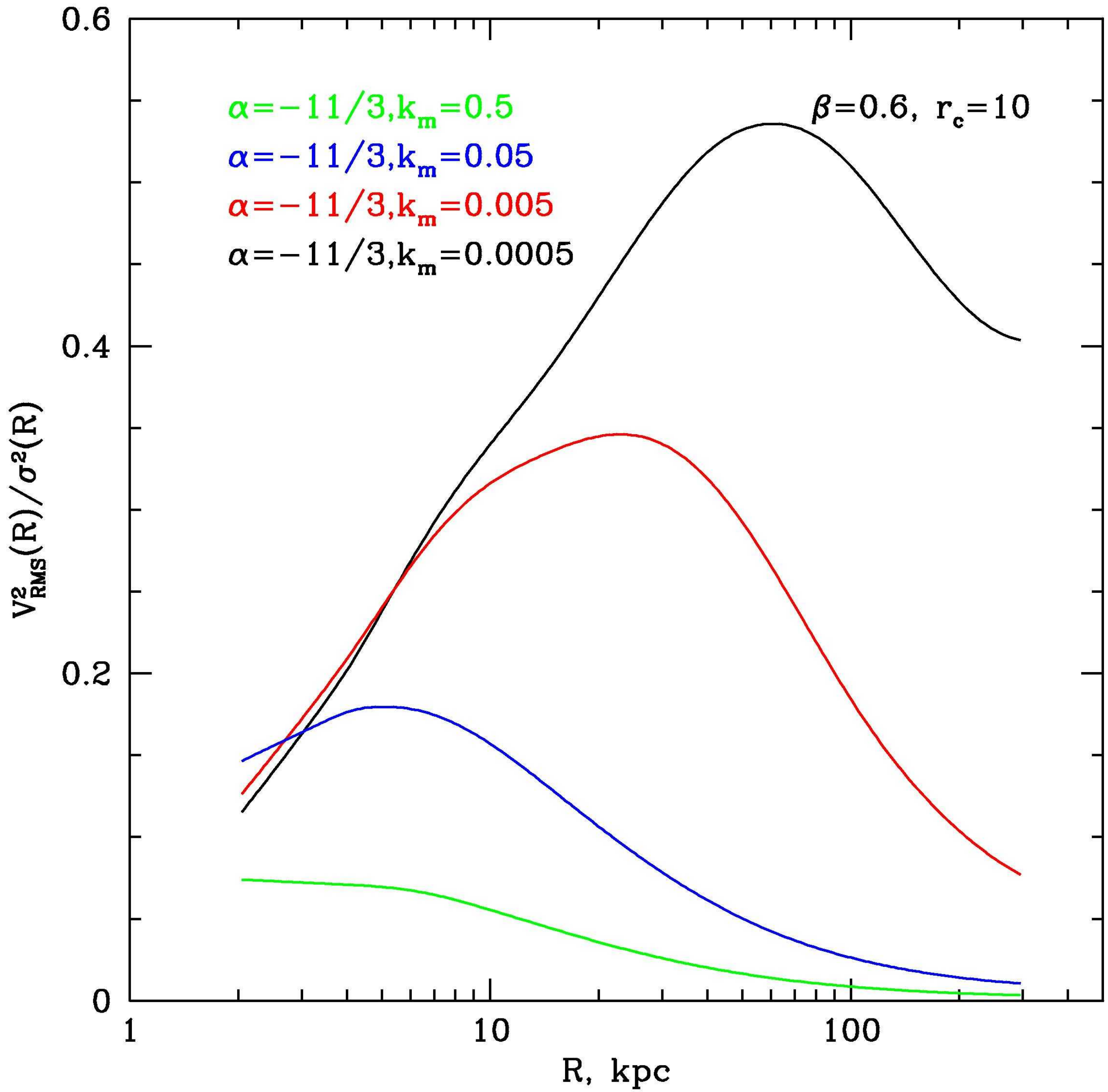
$V_{3D}$ → $L > L_{eff}$ : $V_{2D}$



**RMS(V)/σ — proxy of correlation length**

# RMS and spatial scales of motions



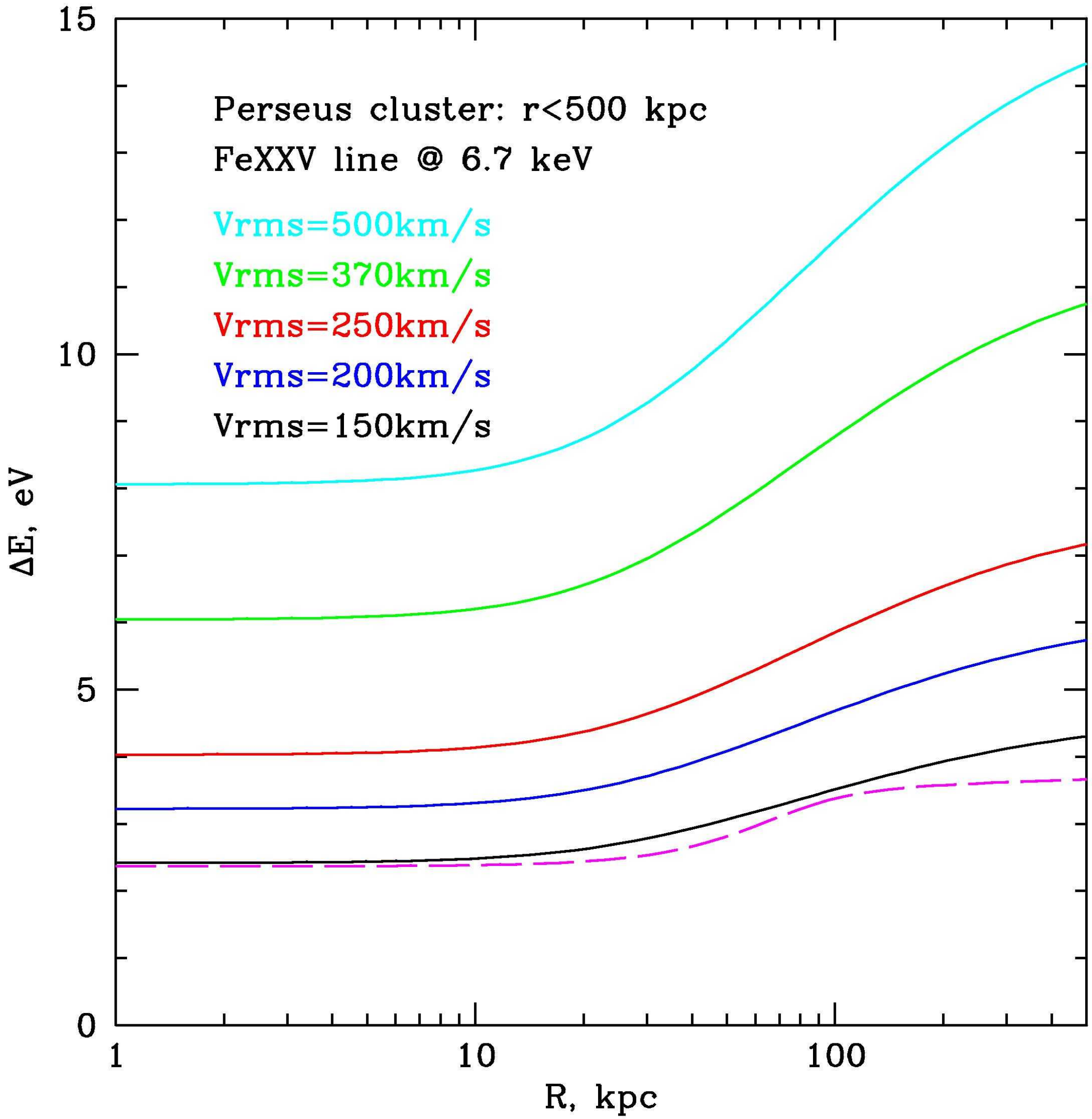



# Conclusions

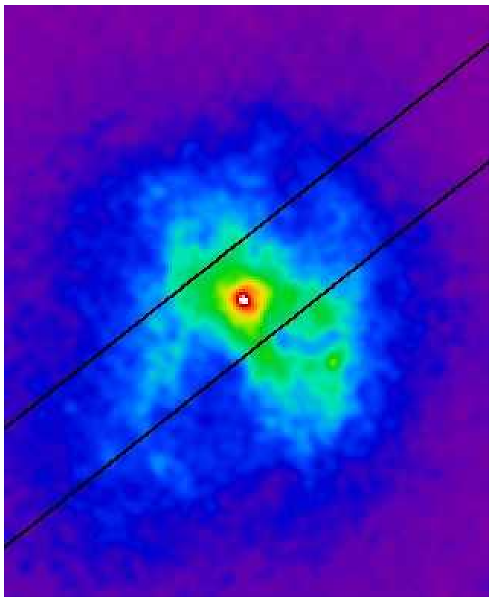
**Direct V measurements (Astro-H, 2014):**

- Shift, width: velocity amplitude
- Width(R): structure function of turbulence
- RMS(shift)/width: correlation length of the velocity field

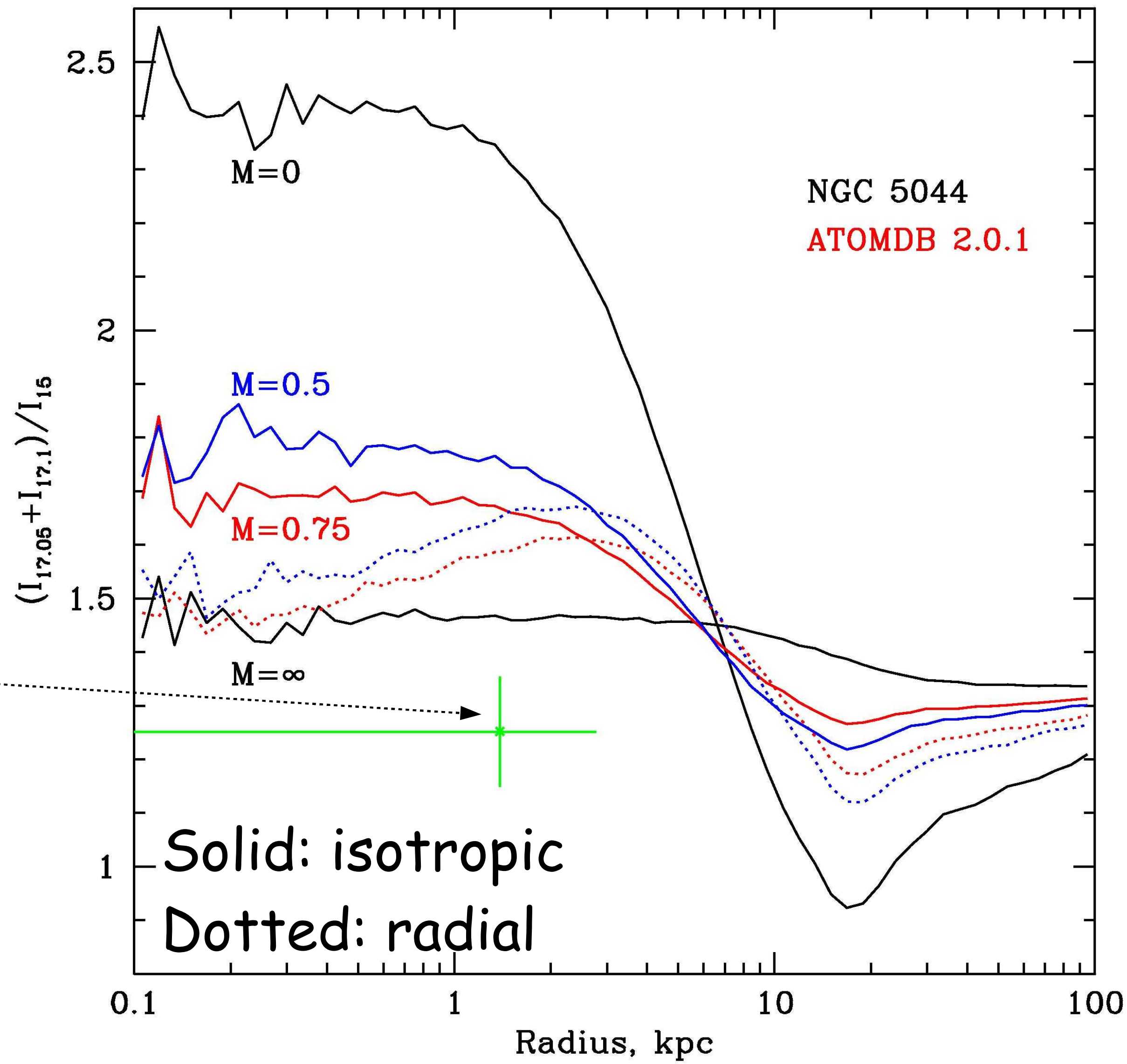
# Perseus cluster: thermal broadening



# Resonant Scattering: NGC 5044



talk of Jelle de Plaa

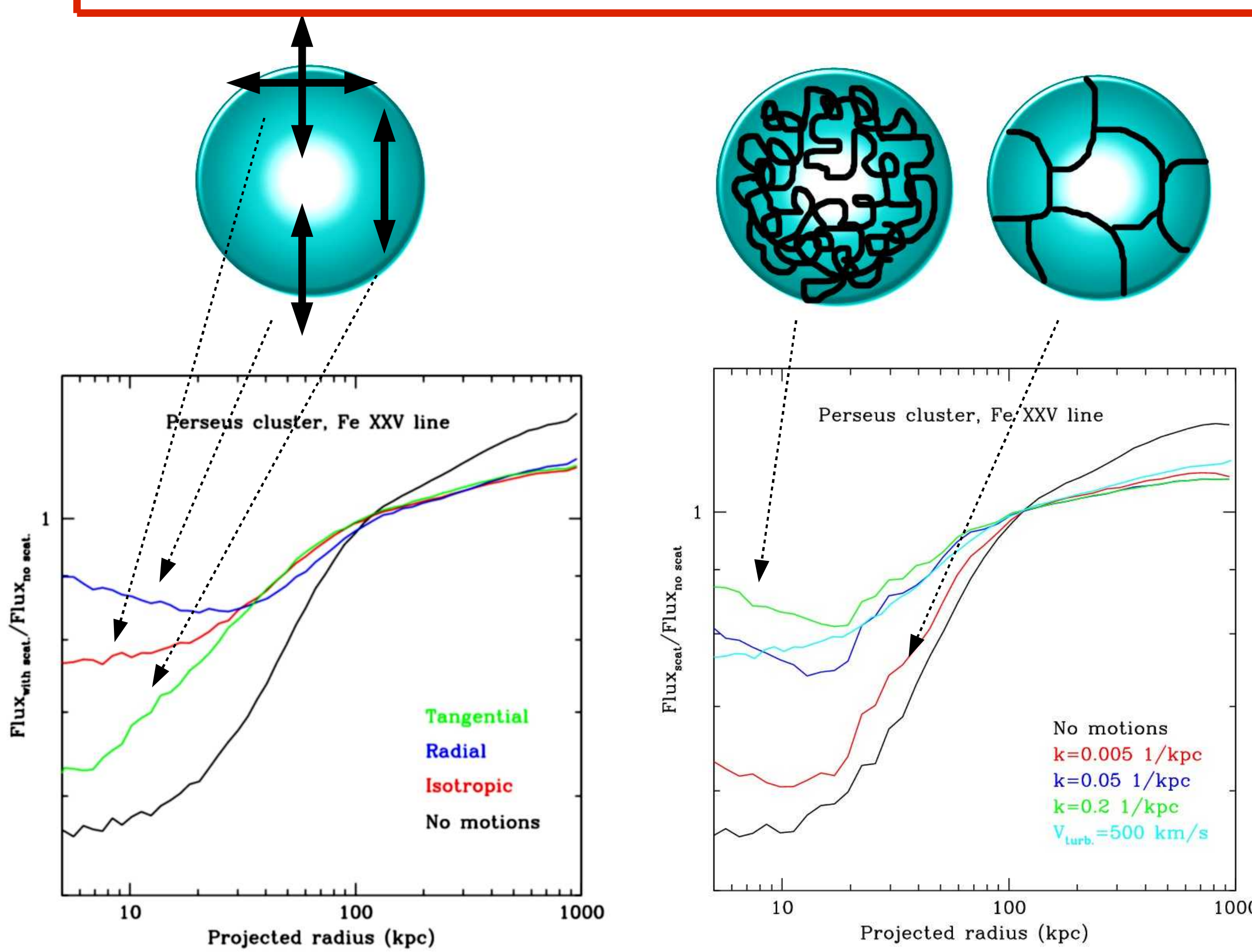


# Resonant scattering

## amplitude + anisotropy + correlation length

(talk by Jelle de Plaa)

$$RS \propto \tau \propto \frac{1}{\Delta E_{\mathrm{D}}} \propto \frac{1}{(V_{\mathrm{therm}}^2 + V_{\mathrm{turb}}^2)^{1/2}}$$




RS is mostly sensitive to:

- radial motions
- small scale motions

Zhuravleva+11a

# Want to know

Amplitudes + spatial scales & anisotropy

# Why?

Mass bias (e.g. Nagai+07, Lau+09)

ICM heating rate (e.g. Churazov+08)

Role in particle acceleration (e.g. Brunetti+06,11)

# How?

Direct/Indirect measurements

# Direct/Indirect measurements

| | XMM-Newton | Chandra | Astro-H (2014) |
|---|---|---|---|
| Width and shift of lines | Weak upper limits on amplitudes (Sanders+11) | - | Amplitudes, spatial scales (Zhuravleva+11b) |
| Resonant Scattering | Upper limits on amplitude (e.g. Werner+09, Churazov+04) talk by Jelle de Plaa | | Amplitudes, spatial scales, anisotropy (Zhuravleva+11a) |
| Pressure fluctuations | Spatial scales (Schuecker+04) | - | - |
| SB fluctuations | Spatial scales talk by E. Churazov | | - |
| Diffusion of heavy elements | Amplitudes, spatial scales Rebusco+06 | | - |

+ X-ray polarization: transverse gas motions (Zhuravleva+10)
+ Kinetic SZ: amplitudes

# Resonant scattering: amplitude of motions

$$\Delta E_D = E_0\left[\frac{2kT}{Am_pc^2}+\frac{V_{turb}^2}{c^2}\right]^{1/2} \rightarrow F_{thin}/F_{thick} \rightarrow V$$

Perseus cluster: V> 400 km/s at r<100 kpc (Churazov+04)

NGC4636: V<100 km/s in the core (Werner+09)

NGC5044, NGC 5813 (talk by Jelle de Plaa)

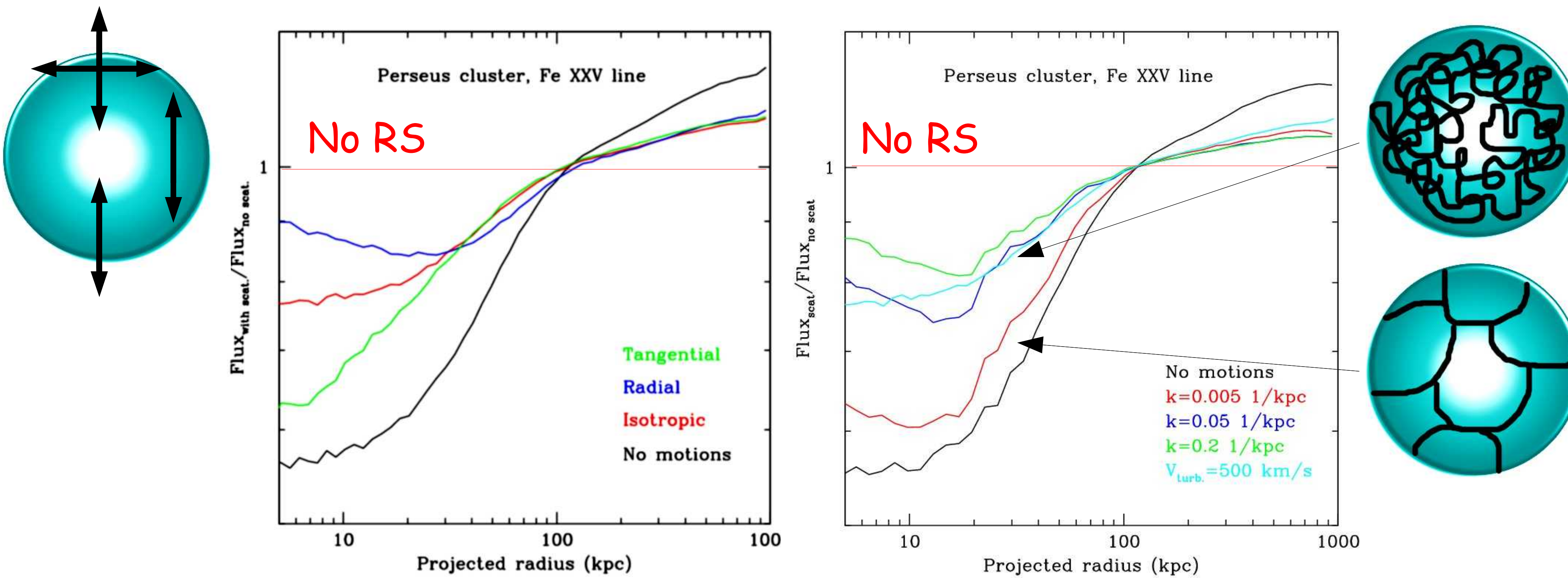
# Resonant Scattering: spatial scales and anisotropy

| Perseus, r<10 kpc | | Perseus, r<30 kpc | |
|---|---|---|---|
| Isotropic: | V=500 km/s | Isotropic: | V=500 km/s |
| Radial: | V=200 km/s | Radial: | V=300 km/s |
| Tangential: | V=1500 km/s | Tangential: | V=1200 km/s |

Zhuravleva+11a

# Resonant Scattering: spatial scales and anisotropy

Optical depth depends on the character of motions



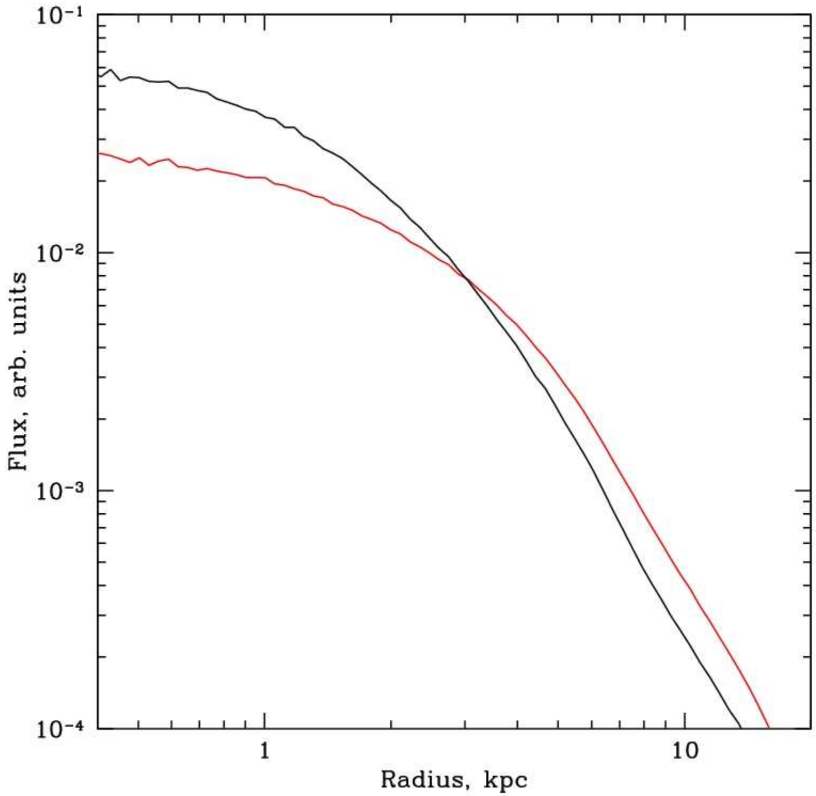

RS is mostly sensitive to:

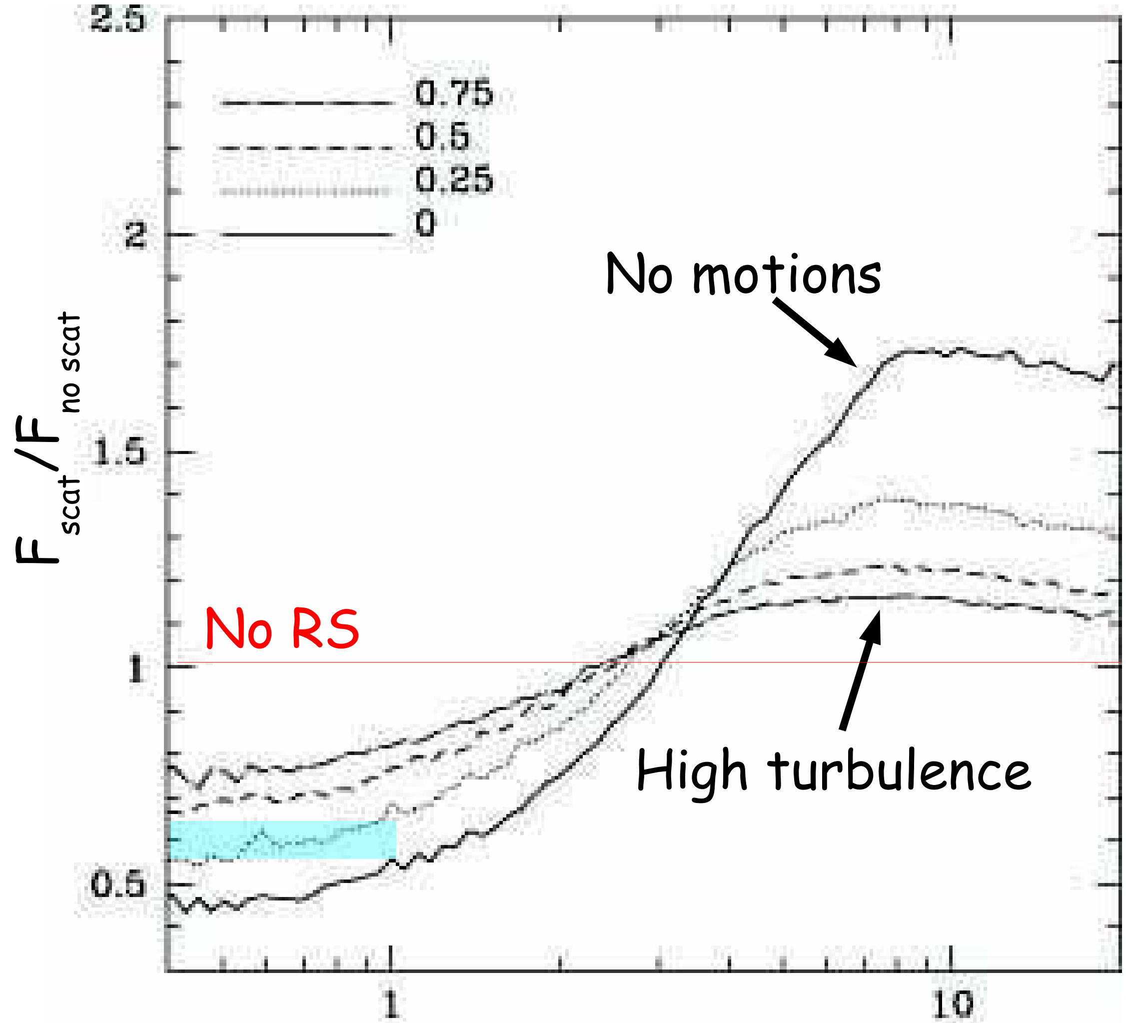
(1) radial motions

(2) small scale motions

Zhuravleva+11a

# Resonant scattering: NGC4636




V in the core < 100 km/s

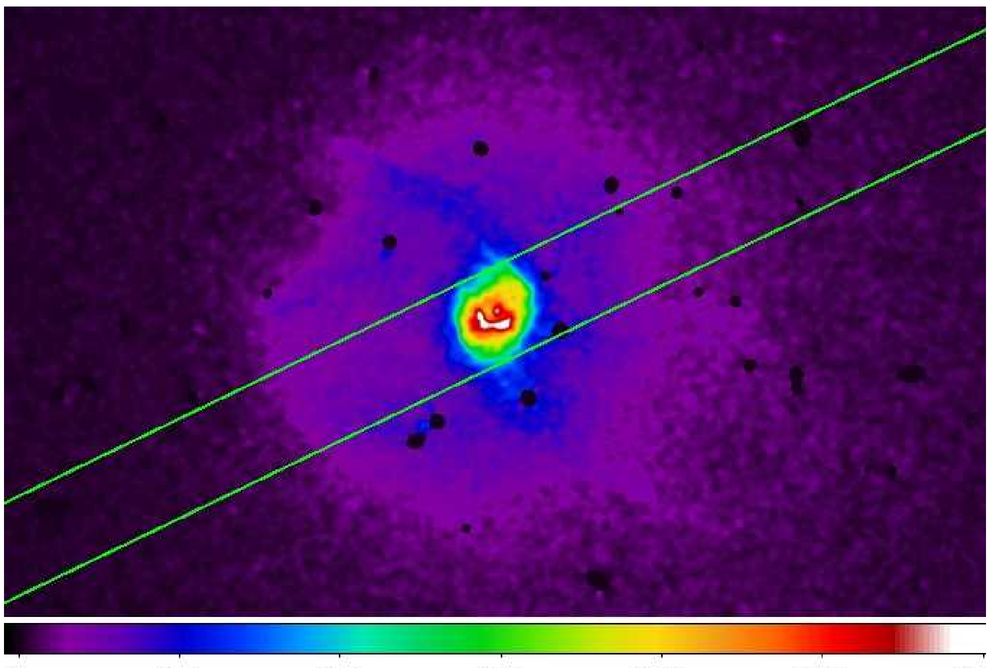
Pressure support < 5% of the thermal P

Werner+09

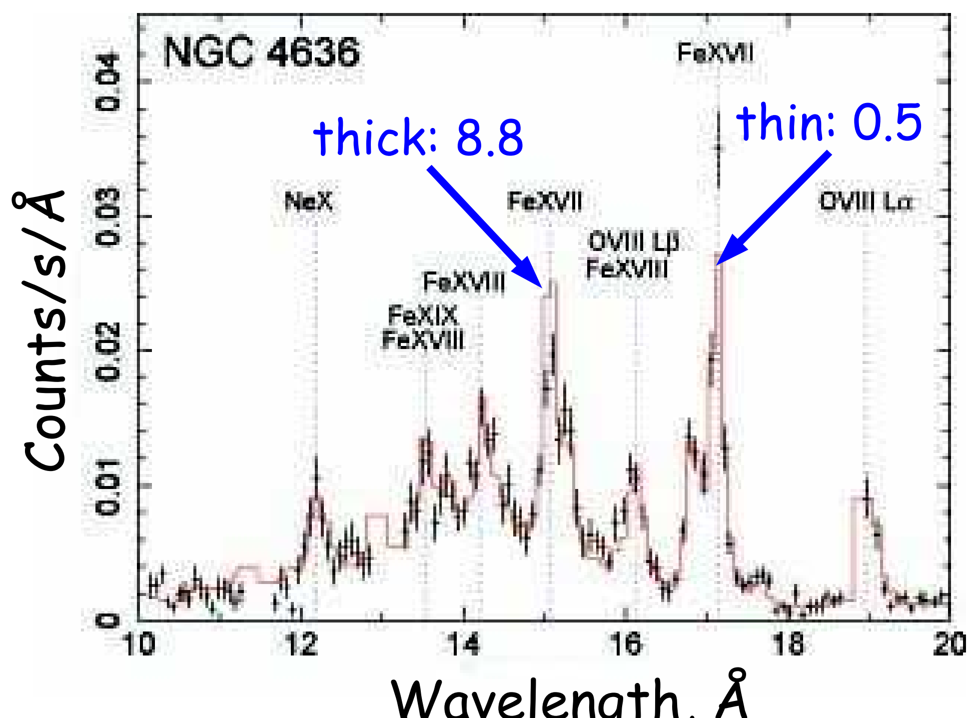
# Resonant scattering: NGC4636

$$\Delta E_D = E_0 \left[ \frac{2kT}{Am_p c^2} + \frac{V_{turb}^2}{c^2} \right]^{1/2} \rightarrow F_{thin} / F_{thick} \rightarrow V$$

NGC4636




RGS XMM Newton 0.5 arcmin




Observations: $F_{17Å}/F_{15Å}=2.04\pm0.21$

Prediction: $F_{17Å}/F_{15Å}=1.31$

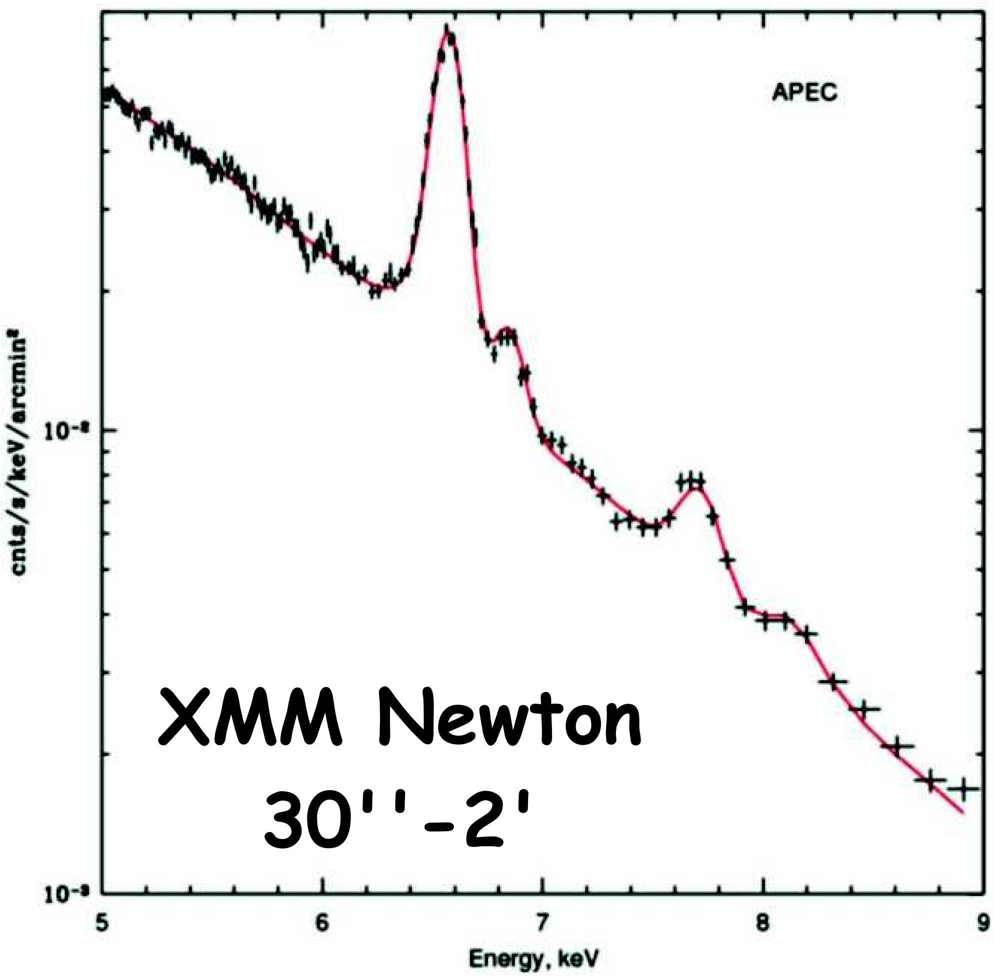
Werner+ 09

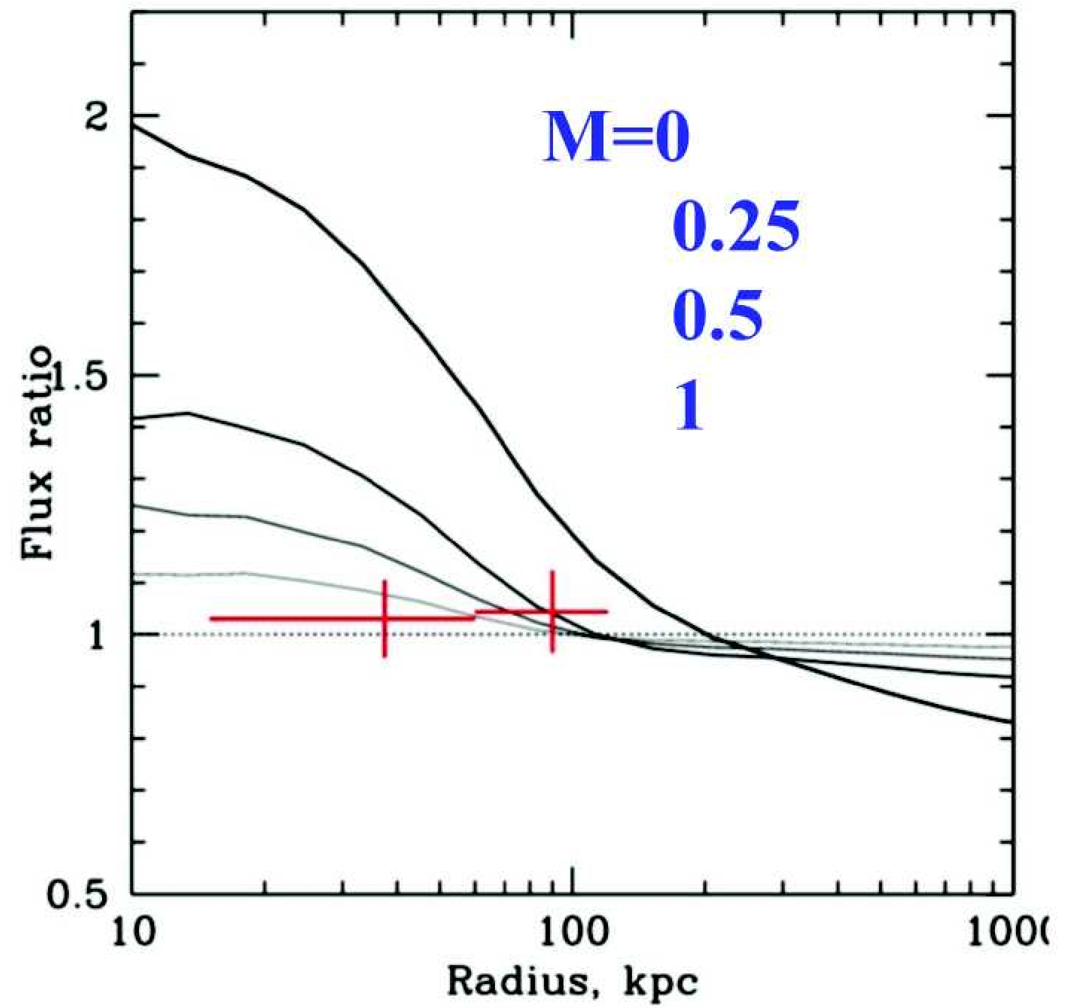
# Resonant scattering: Perseus

He-like Fe 6.7 keV line,

optical depth ~3

$F_{Ni}/F_{Fe}$




6.7 keV line is not supressed → V>400 km/s

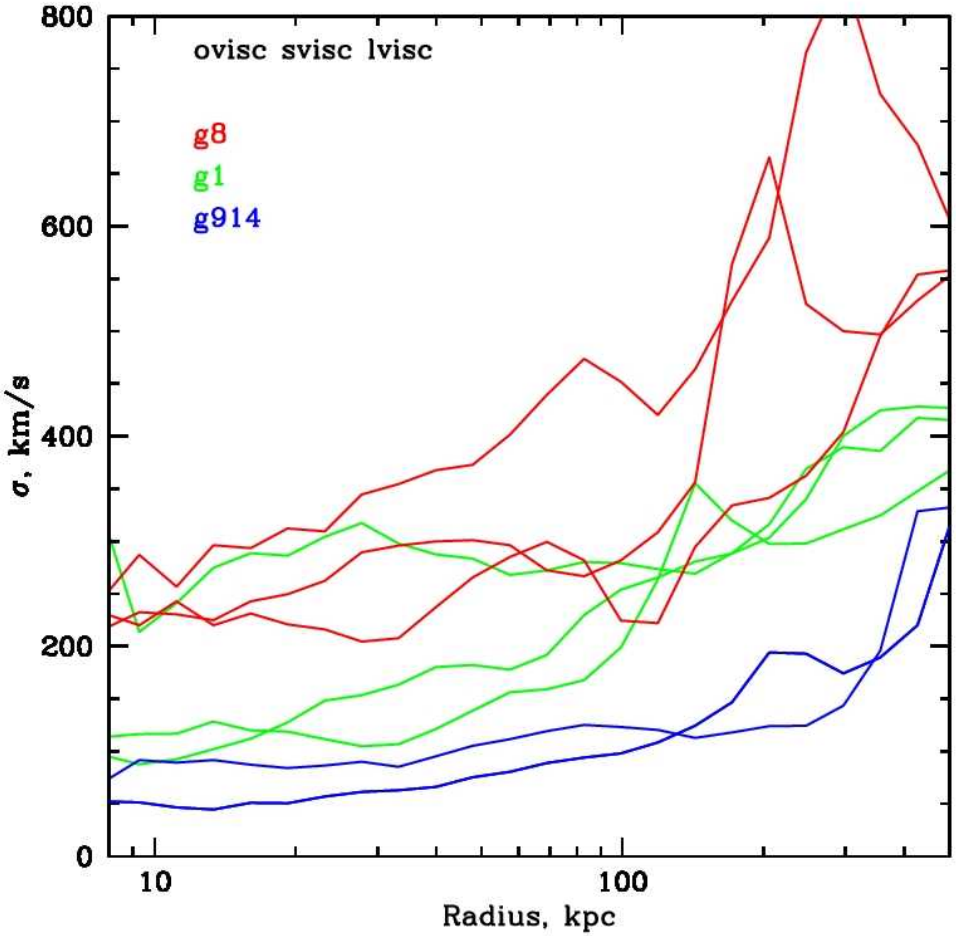
Churazov et al. 2004

# Optical depth in X-ray lines

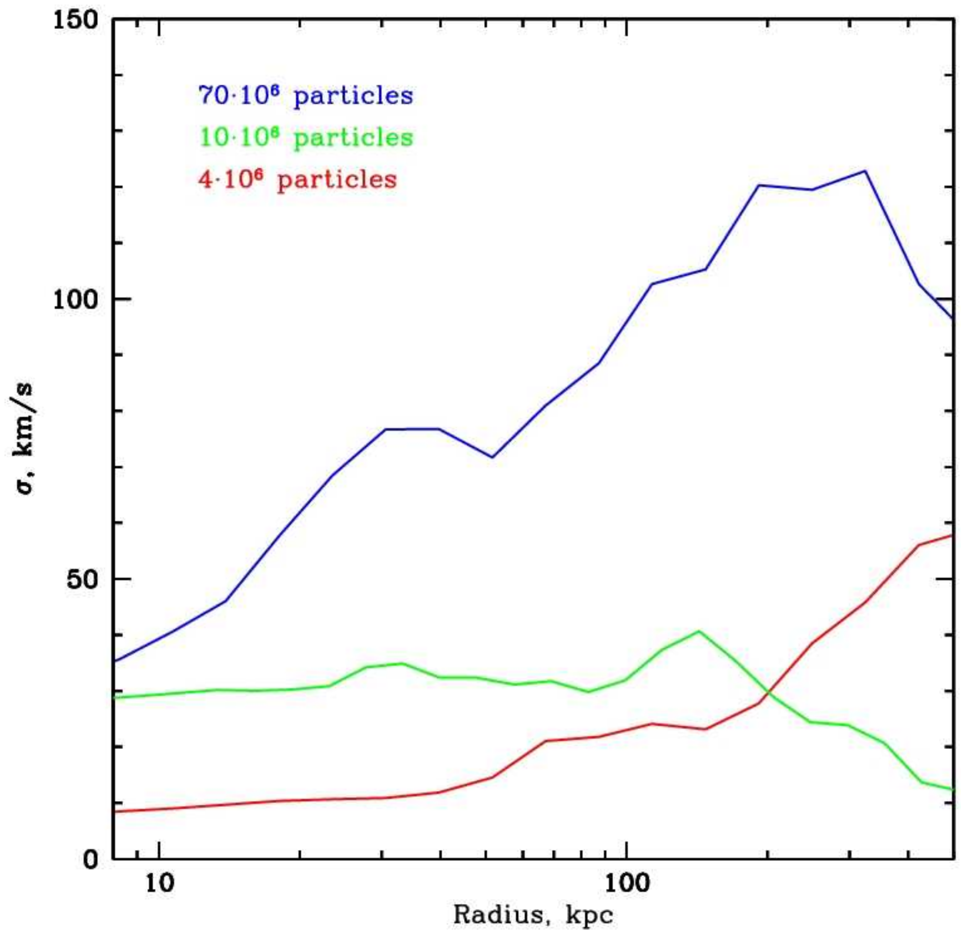
| Ion | $E$, keV | $f$ | $\tau$, NGC 4636 | $\tau$, Virgo/M87 | $\tau$, Perseus |
|---|---|---|---|---|---|
| O VIII | 0.65 | 0.28 | 1.2 | 0.34 | 0.19 |
| Fe XVII | 0.83 | 2.73 | 8.8 | 0.0005 | $2.8 \cdot 10^{-8}$ |
| Fe XVIII | 0.87 | 0.57 | 1.3 | 0.0007 | $1.5 \cdot 10^{-7}$ |
| Fe XXIII | 1.129 | 0.43 | 0.016 | 1.03 | 0.16 |
| Fe XXIV | 1.168 | 0.245 | 0.002 | 1.12 | 0.73 |
| Fe XXV | 6.7 | 0.78 | 0.0002 | 1.44 | 2.77 |

# Velocity field in SPH simulations: main problems

## Numerical viscousity

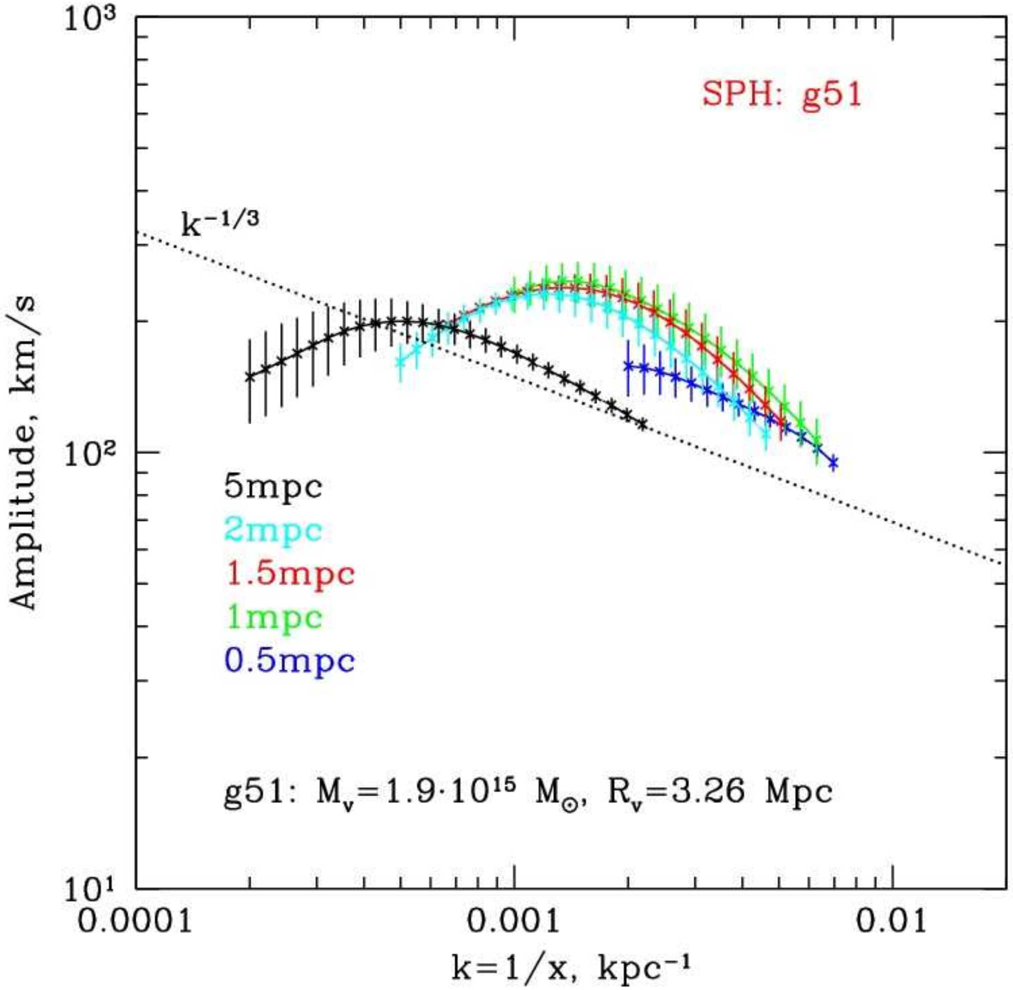


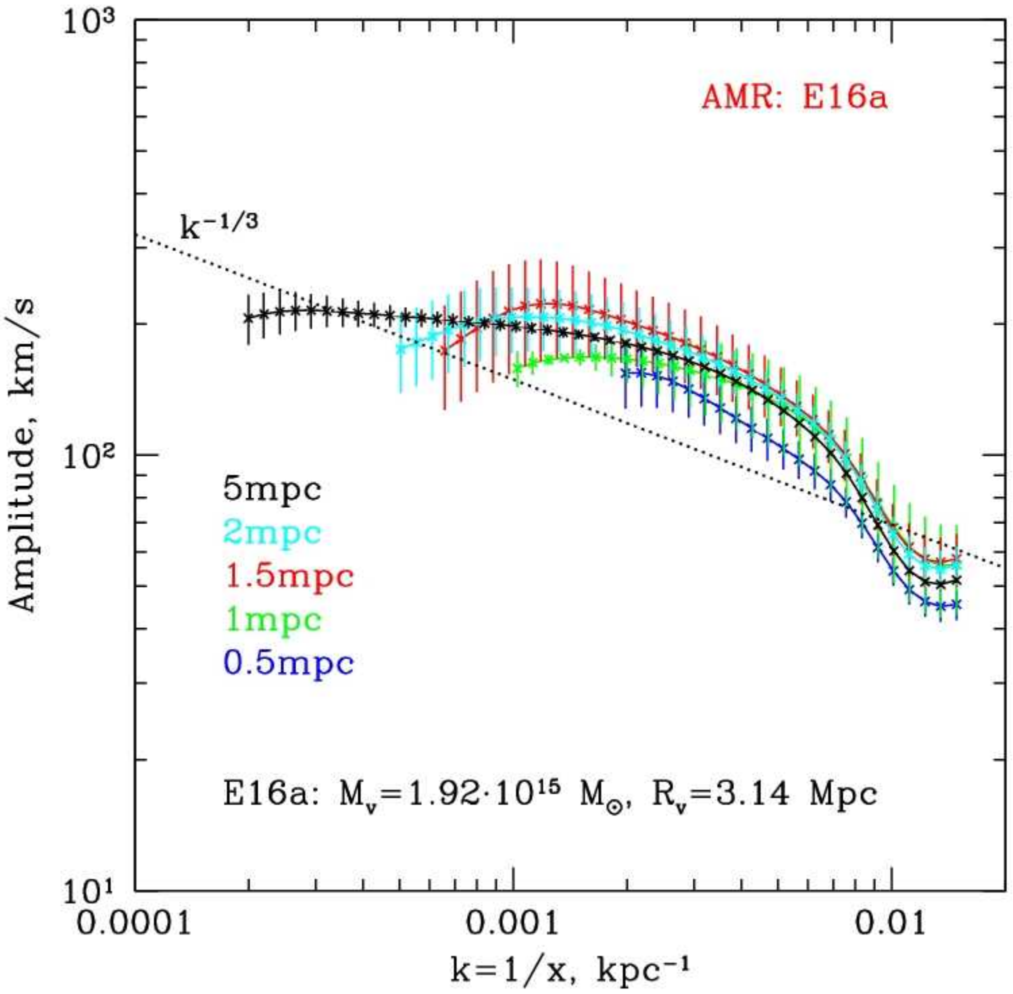

## Resolution




Simulations by Dolag et al. 2005

# 3D velocity power spectrum




Deviations from Kolmogorov PS

Dependence on considered volume

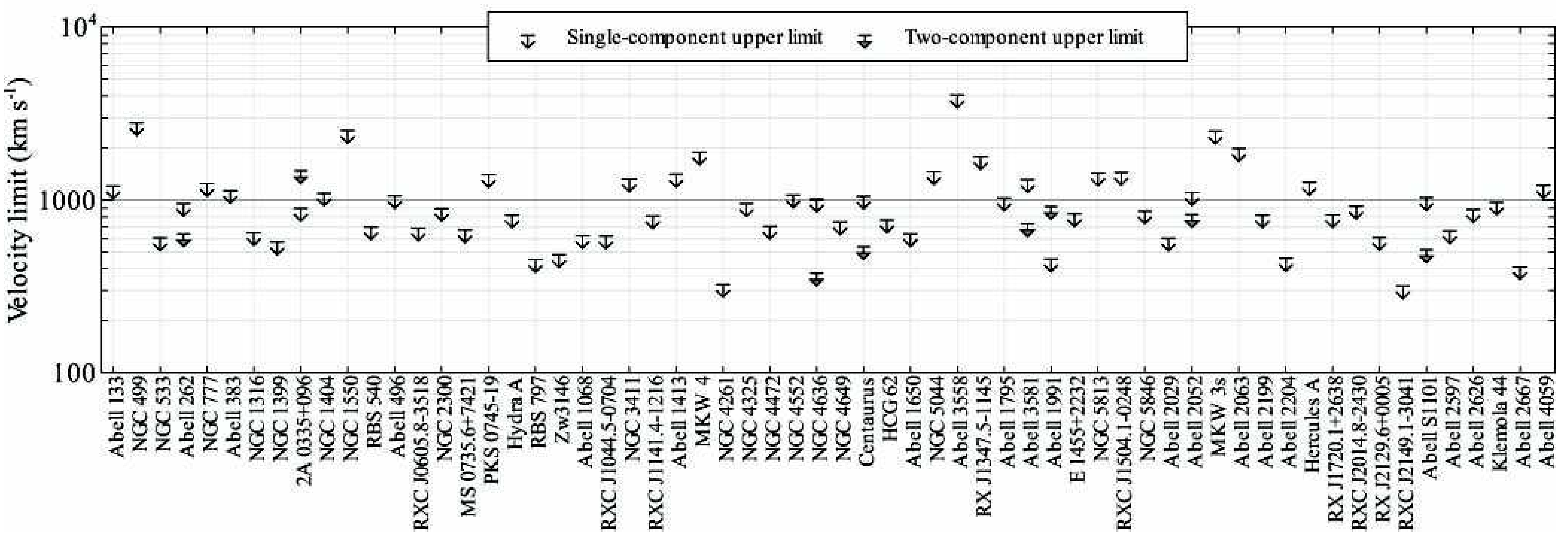
SPH and AMR show similar behaviour

# Gas motions: observations

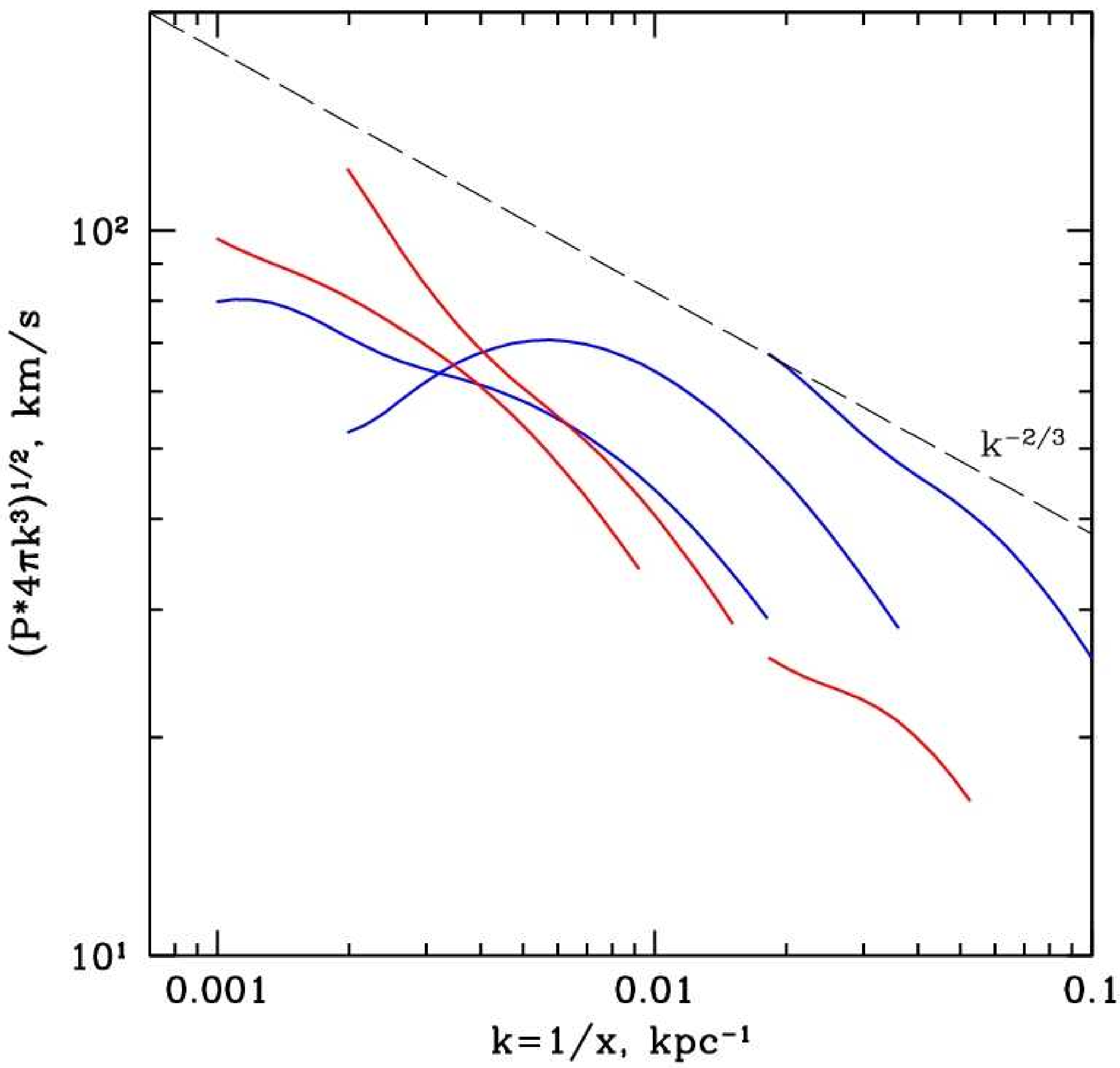
## Broadening and shift of line: amplitude, dispersion

RGS XMM Newton : upper limits on V

(Sanders et al. 2010)



# 3D velocity power spectrum: resolution of simulations



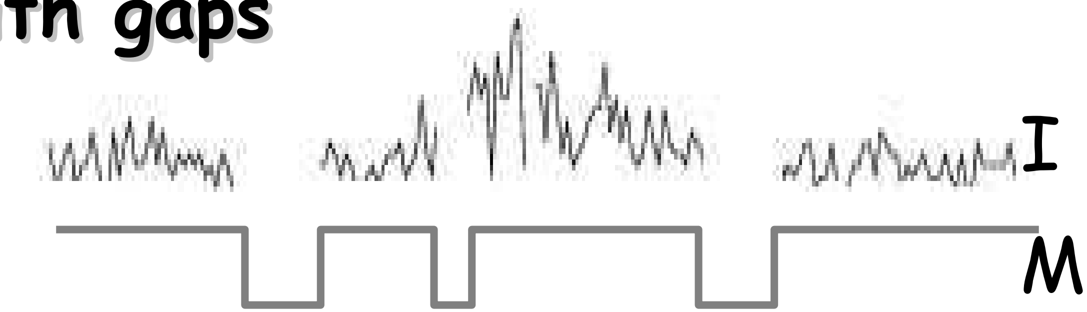
# A Mexican Hat with holes:

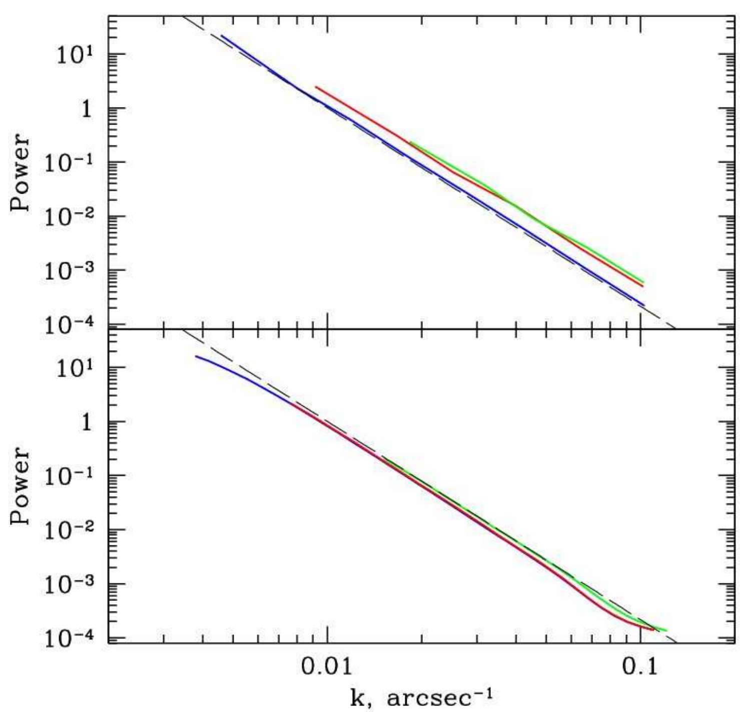
## a method to calculate low resolution PS from data with gaps

Arevalo et al. 2010 in prep.

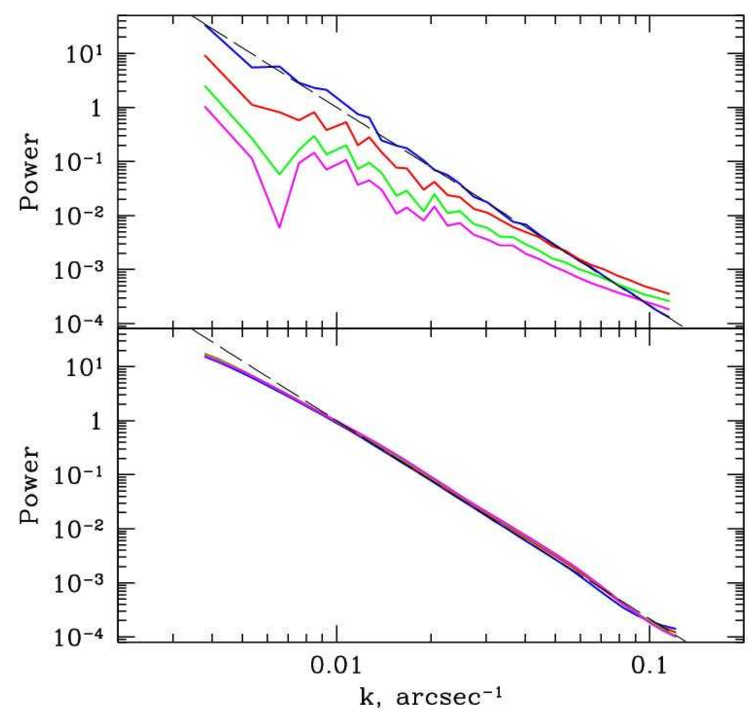
i) $$I_c(k) = \frac{G_{\sigma 1} * I}{G_{\sigma 1} * M} - \frac{G_{\sigma 2} * I}{G_{\sigma 2} * M}$$

ii) variance of $I_c(k)$




trimming of boxes

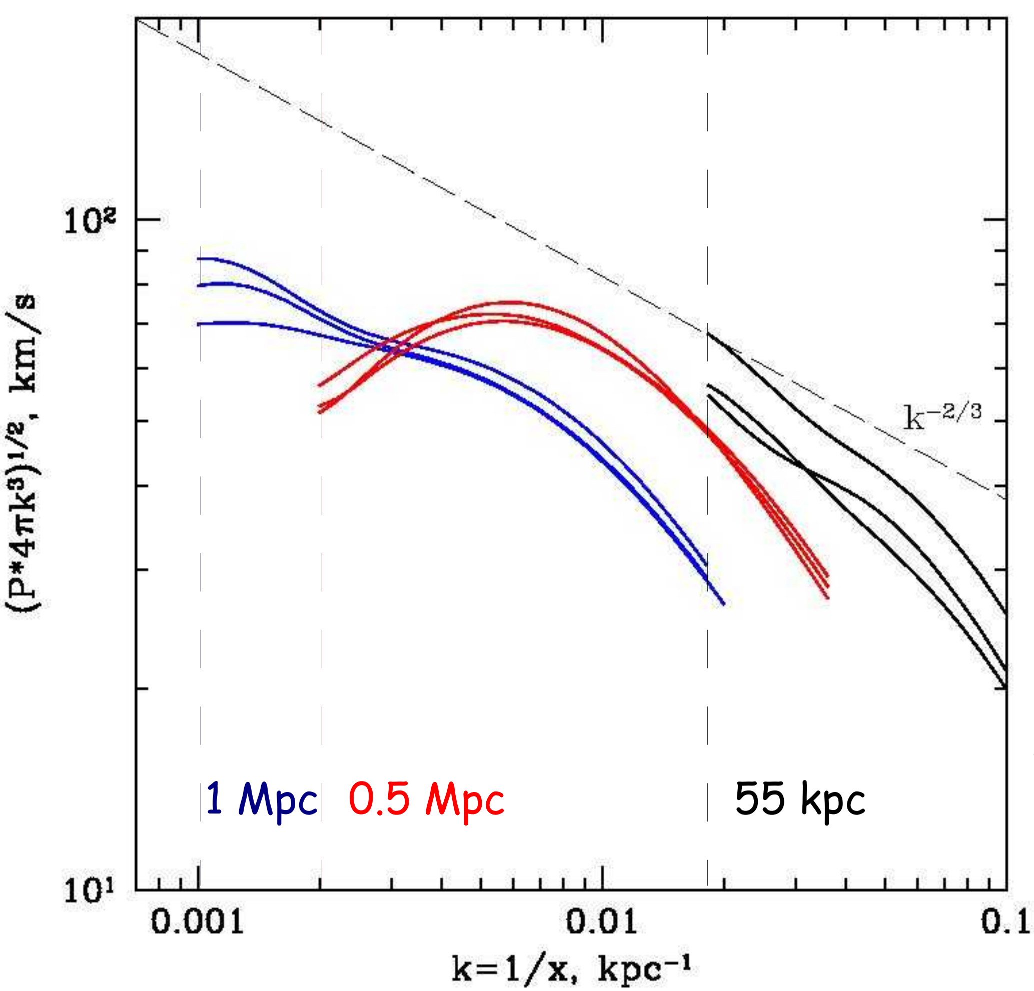


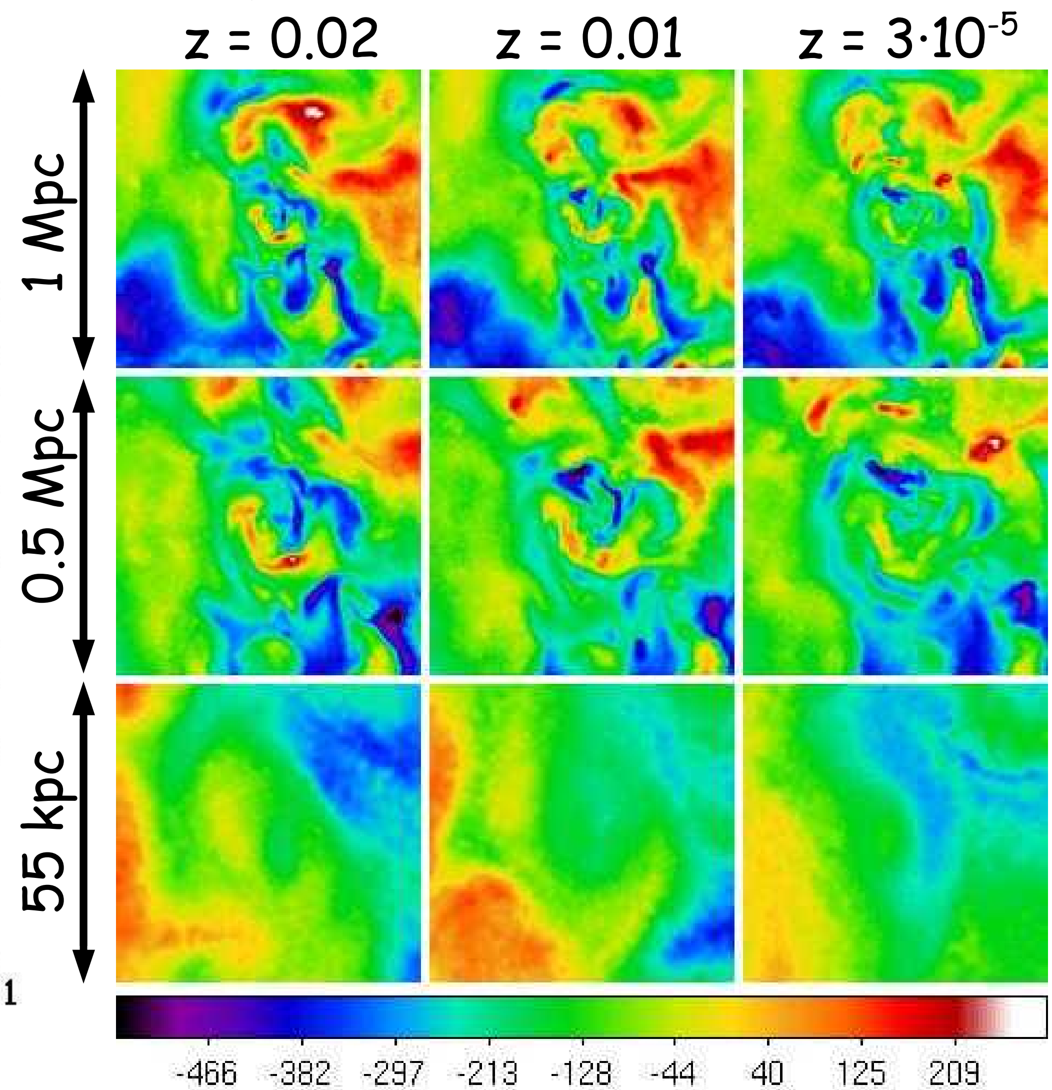

data with gaps

# 3D velocity power spectrum

SPH simulations by K. Dolag (Dolag et al. 2005) , ~ $70 \cdot 10^6$ particles

g676 cluster: $M_{vir}=1.6 \cdot 10^{14}$ $M_{sun}$, $R_{vir}=1.43$ Mpc




**Does PS depend on considered volume of cluster?**

# Velocity field in the ICM: observational signatures and constraints

- anisotropy of velocity field
- correlation length of velocity field («spatial scales»)

I. Zhuravleva, E. Churazov, A. Kravtsov,
S. Sazonov, R. Sunyaev , J. de Plaa, N. Werner, K. Dolag

Structure in Clusters and Groups of Galaxies in the Chandra Era, Boston 2011